

CATADIOPTRIC PROJECTION SYSTEMS

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FIELD OF THE INVENTION

This invention pertains to catadioptric projection systems suitable for use with ultraviolet light sources and applicable to steppers and microlithography systems for the manufacture of semiconductors and liquid crystal display panels.

BACKGROUND OF THE INVENTION

Semiconductor device geometries continue to grow smaller. Because the manufacture of semiconductor devices requires the transfer of high-resolution circuit patterns be transferred to semiconductor wafers, the microlithography systems that project these circuit patterns onto semiconductor wafers must form high-resolution images.

The resolution of microlithography systems has been improved in several ways. For example, high-resolution microlithography systems use ultraviolet light instead of visible light and have high numerical aperture optical systems.

Various types of high-resolution optical projection systems have been considered for high-resolution microlithography systems. Purely refractive projection systems are inadequate at ultraviolet wavelengths. For wavelengths below 300 nm, only a few optical materials are transmissive and refractive optical elements generally must be made of either synthetic fused quartz or fluorite. Unfortunately, combining optical elements of synthetic fused quartz and fluorite is ineffective in eliminating chromatic aberration because the Abbe numbers of synthetic quartz and fluorite are not sufficiently different. Therefore, refractive optical systems for wavelengths less than about 300nm suffer from unacceptable levels of chromatic aberration.

Fluorite itself suffers from several disadvantages. The refractive index of fluorite changes relatively rapidly with temperature and fluorite polishes poorly. Therefore, most ultraviolet optical systems do not use fluorite, and thus exhibit uncorrected chromatic aberration.

Purely reflective projection systems avoid these difficulties, but a reflective projection system typically requires a large diameter mirror; frequently, the mirror must be aspheric. Because the manufacture of precision aspheric surfaces is extremely difficult, a reflective projection system using an aspheric mirror is prohibitively expensive.

Catadioptric projection systems have also been used. A catadioptric projection system is a projection system that uses both reflective elements (mirrors) and refractive elements (lenses). Many catadioptric projection systems for microlithography systems form at least one intermediate image within the optical system. Examples include the catadioptric projection systems of Japanese laid-open patent documents 5-25170 (1993), 63-163319 (1988), and 4-234722 (1992), and U.S. Pat. No. 4,779,966.

Japanese laid-open patent document 4-234722 (1992) and U.S. Pat. No. 4,779,966 describe catadioptric projection systems comprising a concave mirror and double-pass lens groups having negative power. In these systems, an incident light beam propagates through the double-pass lens group in a first direction, strikes the concave mirror, and then propagates as a reflected light beam through the double-pass lens group in a second direction opposite to the first direction. In these prior-art systems, the double-pass lens groups have negative power. For this reason, light incident to the concave mirror is divergent and the diameter of the concave mirror must be large.

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The double-pass optical system of Japanese laid-open patent document 4-234722 (1992) is symmetric; aberrations in this optical system are extremely low, simplifying aberration correction in the subsequent refractive optical system. However, because it is symmetric, the optical system has a short working distance. In addition, because it is difficult with this system to separate the incident light beam and the reflected light beam, a beamsplitter is required. The preferable location for the beamsplitter in such a projection system is near the concave mirror. Consequently, the beamsplitter is large, heavy, and expensive.

The optical system of U.S. Pat. No. 4,779,966 comprises a concave mirror in a second imaging system. In this system, diverging light enters the concave mirror and the concave mirror must have a large diameter.

Optical systems comprising more than one mirror can use fewer lenses than a purely refractive optical system, but other problems arise. In order to increase resolution and depth of focus, phase-shift masks are frequently used. In order to effectively use a phase-shift mask, the ratio of the numerical aperture of the irradiation optical system and the numerical aperture of the projection system should be variable. While an adjustable aperture is easily located in the irradiation optical system, a catadioptric projection system usually has no suitable location for a corresponding aperture, adjustable or not.

In a catadioptric projection system in which a double-pass lens group is placed within a demagnifying portion of the optical system, the demagnification reduces the distance between the reflecting elements and the semiconductor wafer. This limits the number of lens elements that can be inserted in the optical path, and thus limits the numerical aperture of the projection system and the total optical power available to expose the wafer. Even if a high numerical aperture is possible, the working distance (i.e., the distance between the wafer and the most imagewise surface of the optical system) is short.

Prior-art catadioptric projection systems have optical elements arranged along more than one axis, using prisms or mirrors to fold the optical pathway. The alignment of optical elements in a system with more than one axis is expensive and difficult, especially when high resolution is required. Prior-art catadioptric projection systems are also difficult to miniaturize while simultaneously maintaining image quality. In addition, in a miniaturized prior-art catadioptric projection system, the beam-separation mirror that separates the incident light beam from the reflected light beam is likely to obstruct one of these beams.

Increasing the magnification of the intermediate image and moving the beam-separation mirror away from the optical axis have been considered as solutions to this problem. However, changing the magnification of the intermediate image requires changes to the remainder of the optical system to maintain an appropriate magnification on the wafer. This causes loss of image quality.

Moving the beam-separation mirror away from the optical axis without changing the magnification of the intermediate image can be accomplished by using light beams propagating farther off-axis and increasing the diameter of the projection system. Both of these changes are undesirable, leading to a larger, heavier projection system with less resolution.

Some prior-art catadioptric projection systems are used in full-field exposure systems in which patterns from an entire reticle are projected onto the wafer in a single exposure. Examples include the catadioptric projection systems of

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In view of the foregoing, improved catadioptric projection systems for microlithography systems are needed.

This invention provides catadioptric projection systems that are readily miniaturized while maintaining image quality. A catadioptric projection system according to this invention comprises a first imaging system and a second imaging system. The first imaging system comprises a single-pass lens group and a double-pass lens group including a concave mirror. Light from an illuminated region of the reticle returns through the single-pass lens group and then enters the double-pass lens group. Light propagates through the double-pass lens group in a first direction, strikes the concave mirror, and then returns through the double-pass lens group in a second direction opposite the first direction. A turning mirror is provided between the single-pass lens group and the double-pass lens group. In some embodiments of the invention, the turning mirror directs the light from the first imaging system (after reflection by the concave mirror and back through the double-pass lens group) to the second imaging system. In alternative embodiments of the invention, the turning mirror directs light exiting the single-pass lens group to the double-pass lens group. The first imaging system forms an intermediate image of the illuminated region of the reticle near the turning mirror; the second imaging system re-images the intermediate image and forms an image of the illuminated region of the reticle on a substrate, typically a semiconductor wafer.

In such catadioptric projection systems, the diameter of the concave mirror can be kept small, the ratio of the imaging-optical-system numerical aperture and the illumination-optical-system numerical aperture σ can be variable, and an appropriate location is available for an aperture if phase-shift masks are used. In addition, such catadioptric projection systems have high numerical apertures and hence provide sufficient irradiation to the wafer as well as conveniently long working distances.

The second imaging system comprises a first lens group and a second lens group.

The single-pass lens group comprises, in order starting at the reticle, a first negative subgroup, a positive subgroup, and a second negative subgroup. Single-pass optical groups with this configuration are compact, produce high-resolution images, and permit separation of incident and reflected light beams. The magnification of the first imaging system can be selected as appropriate while still maintaining excellent optical performance. Thus, the magnification of the intermediate image can be varied. Preferably, either the first imaging system or the second imaging system demagnifies the reticle. Obtaining a demagnification using the first imaging system simplifies the second imaging system.

The foregoing and other objects, features, and advantages of the invention will become more apparent from the following detailed description which proceeds with reference to the accompanying drawings.

FIG. 7 is a general schematic representation of a prior-art optical system.

In order to describe the invention, a representation of a prior-art optical system is first described with reference to FIG. 7. A ray 102 from a location on a reticle R a distance d from an optical axis 100 is incident on a lens group A₁. The lens group A₁ comprises, in order from the reticle R and along the optical axis 100, a positive subgroup A₁₂ and a negative subgroup A₁₁. The lens group A₁ bends the ray 102

The double-pass lens group A_2 is placed along the optical axis 210 and receives light from the single-pass lens group A_1 and directs light to a concave mirror M_1 of the double-pass optical group A_2 , placed on the optical axis 210. The concave mirror M_1 reflects light back through the double-

pass lens group A_2 . After passing through the double-pass lens group A_2 , the light forms an image near the turning mirror M_2 . The turning mirror M_2 reflects light from the first imaging system A to the second imaging system B. The turning mirror M_2 directs light propagating along the optical axis 210 to propagate along an optical axis 211 of the second imaging system.

The second imaging system B comprises, beginning near the turning mirror M_2 and proceeding along the optical axis 211, a first lens group B_1 and a second lens group B_2 . An aperture S is placed between the first lens group B_1 and the second lens group B_2 .

FIG. 3 shows the optical system of the first embodiment in detail. For clarity, the folded optical path caused by the concave mirror M_1 and the turning mirror M_2 has been unfolded by inserting virtual flat mirrors immediately behind the concave mirrors M_1 and the turning mirror M_2 . These virtual mirrors are not actually part of the first example embodiment but serve to simplify FIG. 3. Such an unfolded representation of a catadioptric optical system will be readily understood by persons of ordinary skill in the art.

Table 1 contains specifications for the first example embodiment. In Table 1, the first column lists surface numbers, numbered from the reticle R to the wafer W. Surface numbers relevant to this discussion are specifically denoted in FIG. 3. The second, third, and fourth columns of Table 1 list the radii of curvature of the optical surfaces ("r"), surface separations ("d") along the optical axis, and the lens material, respectively. The fifth column indicates the group number for each of the optical elements. Distances are in mm. Some of the surfaces of Table 1 represent plane mirrors and other planar surfaces used to simplify FIG. 3; such surfaces do not represent actual optical elements.

Table 1 lists the elements of the double-pass lens group A_2 twice. Surfaces indicated as part of the lens group A_2 are surfaces through which pass light propagates immediately after propagating through the single-pass lens group A_1 ; the same surfaces through which the light propagates immediately after reflection from the concave mirror M_1 are indicated as belonging to the lens group A_2^* . As will be apparent, the concave mirror M_1 is included only once.

The lenses of the first embodiment are made of synthetic fused quartz (SiO_2) and fluorite (CaF_2). Axial chromatic aberration and chromatic difference of magnification (lateral color) are corrected for a wavelength range of ± 0.1 nm about a wavelength of 193 nm for use with an ultraviolet excimer laser emitting at a wavelength of 193 nm. The Abbe numbers v_{193} given are for fluorite and synthetic fused quartz at wavelengths of 193 nm ± 0.1 nm instead of the customary visible wavelengths; the refractive indices n are for a wavelength of 193 nm.

As specified in Table 1, the optical projection system of the first example embodiment provides a demagnification of the reticle R on the wafer W of $1/4$, a wafer-side numerical aperture of 0.6, and covers a span of 76 mm of the reticle R.

TABLE 1

(First Example Embodiment)		
Lens Material Properties		
Material	Index of Refraction (n)	Abbe Number v_{193}
Fused Quartz (SiO_2)	1.56019	1780
Fluorite (CaF_2)	1.50138	2550

(First Example Embodiment)

(First Example Embodiment)				
Optical System Specifications				
Surf. No.	r	d	Material	Group
0	-	70.000000		R
1	-497.01528	15.000000	CaF ₂	A ₁₁
2	-2089.03221	0.100000		
3	4955.40172	35.000000	SiO ₂	A ₁₁
4	-684.52303	0.100000		
5	373.53254	40.000000	SiO ₂	A ₁₂
6	-458.84391	32.494228		
7	-384.75862	15.000000	SiO ₂	A ₁₃
8	399.06352	11.499839		
9	∞	0		
10	∞	15.000000		
11	∞	0		
12	∞	30.000000		
13	∞	0		
14	∞	15.805933		
15	360.53651	60.000000	CaF ₂	A ₂
16	-357.18478	1.000000		
17	-410.75622	15.000000	SiO ₂	A ₂
18	272.78252	3.000000		
19	264.76319	55.000000	CaF ₂	A ₂
20	-403.51844	8.000000		
21	-313.01237	15.000000	SiO ₂	A ₂
22	-536.13663	141.754498		
23	753.93969	16.200000	SiO ₂	A ₂
24	350.20343	24.941513		
25	502.28185	22.500000	SiO ₂	A ₂
26	1917.58499	72.939269		
27	696.45818	25.920000	CaF ₂	A ₂
28	422.44154	45.000000		
29	-165.29930	15.000000	SiO ₂	A ₂
30	-247.15361	7.435035		
31	447.76970	40.000000	SiO ₂	A ₂
32	-650.53438	176.819005		
33	-207.03257	15.000000	SiO ₂	A ₂
34	3807.25755	27.000000		
35	∞	0		
36	316.26451	27.000000	(M ₁)	A ₂
37	-3807.25755	15.000000	SiO ₂	A ₂ *
38	207.03257	176.819005		
39	650.53438	40.000000	SiO ₂	A ₂ *
40	-447.76970	7.435035		
41	247.15361	15.000000	SiO ₂	A ₂ *
42	165.29930	45.000000		
43	-422.44154	25.920000	CaF ₂	A ₂ *
44	-696.45818	72.939269		
45	-1917.58499	22.500000	SiO ₂	A ₂ *
46	-502.28185	24.941513		
47	-350.20343	16.200000	SiO ₂	A ₂ *
48	-753.93969	141.754498		
49	536.13663	15.000000	SiO ₂	A ₂ *
50	313.01237	8.000000		
51	403.51844	55.000000	CaF ₂	A ₂ *
52	-264.76319	3.000000		
53	-272.78252	15.000000	SiO ₂	A ₂ *
54	410.75622	1.000000		
55	357.18478	60.000000	CaF ₂	A ₂ *
56	-360.53651	15.805933		
57	∞	0		
58	∞	30.000000		
59	∞	0		
60	∞	130.000000		M ₂
61	408.08942	20.000000	SiO ₂	B ₁
62	203.49020	3.000000		
63	207.52684	30.000000	CaF ₂	B ₁
64	19354.35793	0.1000000		
65	429.85442	35.000000	SiO ₂	B ₁
66	-403.83438	14.478952		
67	-353.07980	15.000000	SiO ₂	B ₁
68	261.24968	31.363884		
69	-219.57807	23.000000	SiO ₂	B ₁
70	-348.23898	1.990938		
71	502.56605	40.000000	CaF ₂	B ₁

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A second example embodiment of the invention is shown in FIG. 5. The optical projection system of FIG. 5 is similar to that of the embodiment of FIG. 2. Light from an illuminated region 321 (FIG. 3(a)) of a reticle R is directed to, beginning nearest the reticle R and along an optical axis 310, a single-pass lens group A₁ comprising a first negative subgroup A_{1,1}, a positive subgroup A_{1,2}

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The catadioptric projection systems of the present invention include several other favorable characteristics. First, a turning mirror (or a beamsplitter) can be placed near the intermediate image, thereby reducing the size of the turning mirror. Second, unlike conventional catadioptric projection systems that allow light reflected by a mirror to overlap with the incident light (which makes placement of the aperture S difficult), the catadioptric projection systems of the present invention allow the aperture S to be placed in the second